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Strange Hadron Production in Au+Au Collisions at RHIC Beam Energy Scan

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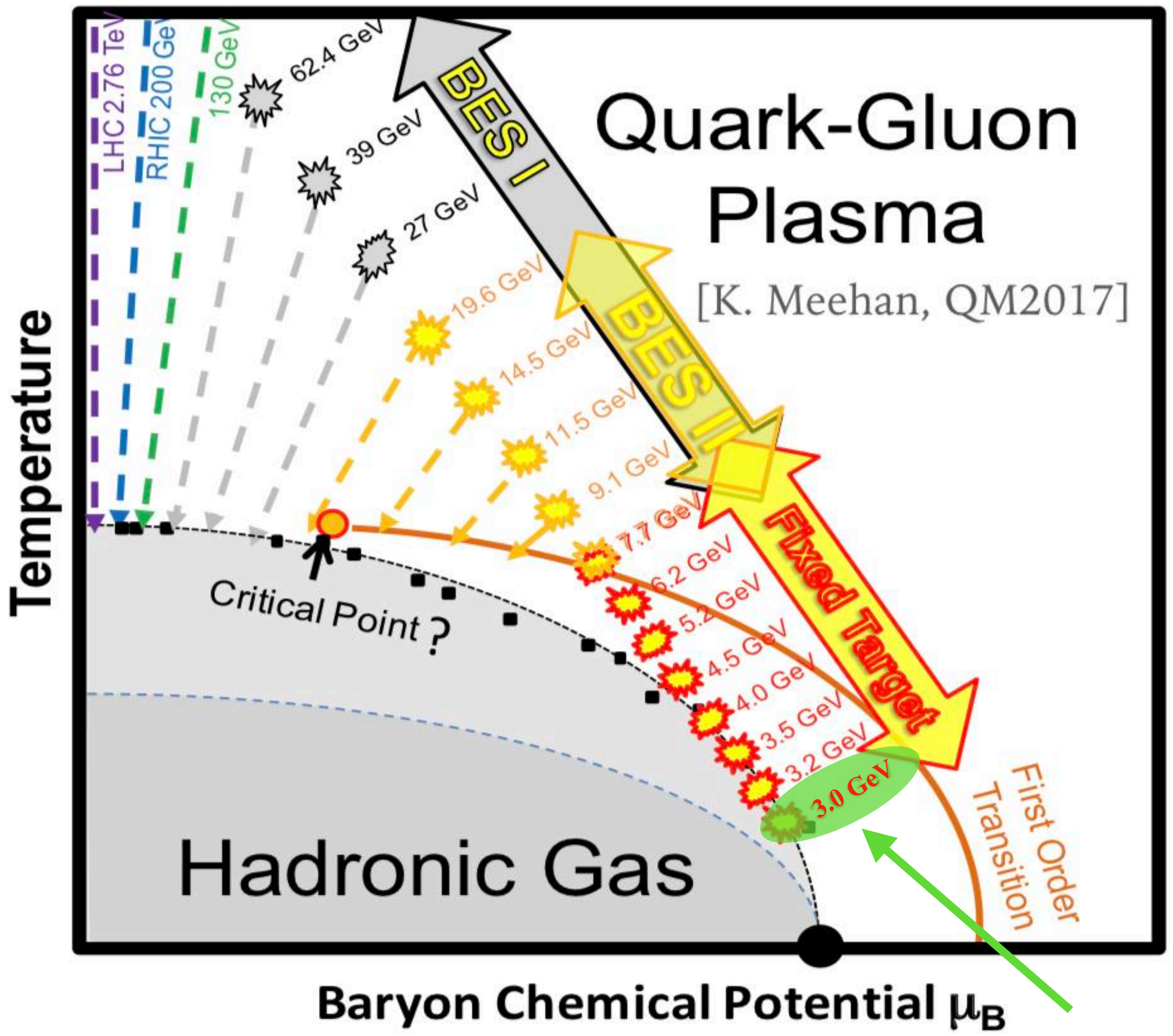
Outline

- **Introduction**
- **STAR Fixed Target (FXT)**
- **Results of strange hadron production**
  - p_T spectra
  - Rapidity distribution
  - Yield ratio
  - Kinetic freeze-out properties
- **Summary**

Introduction

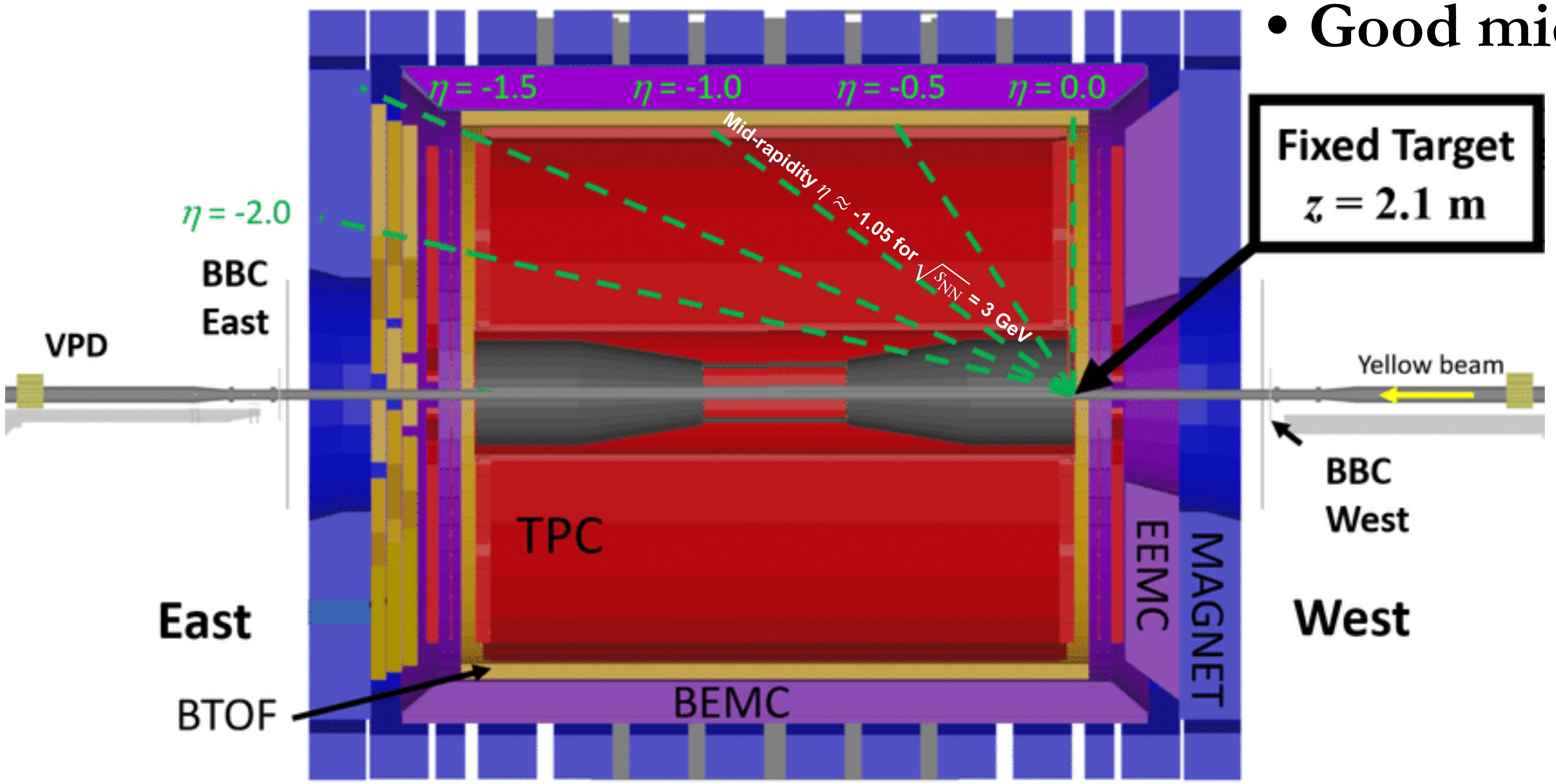


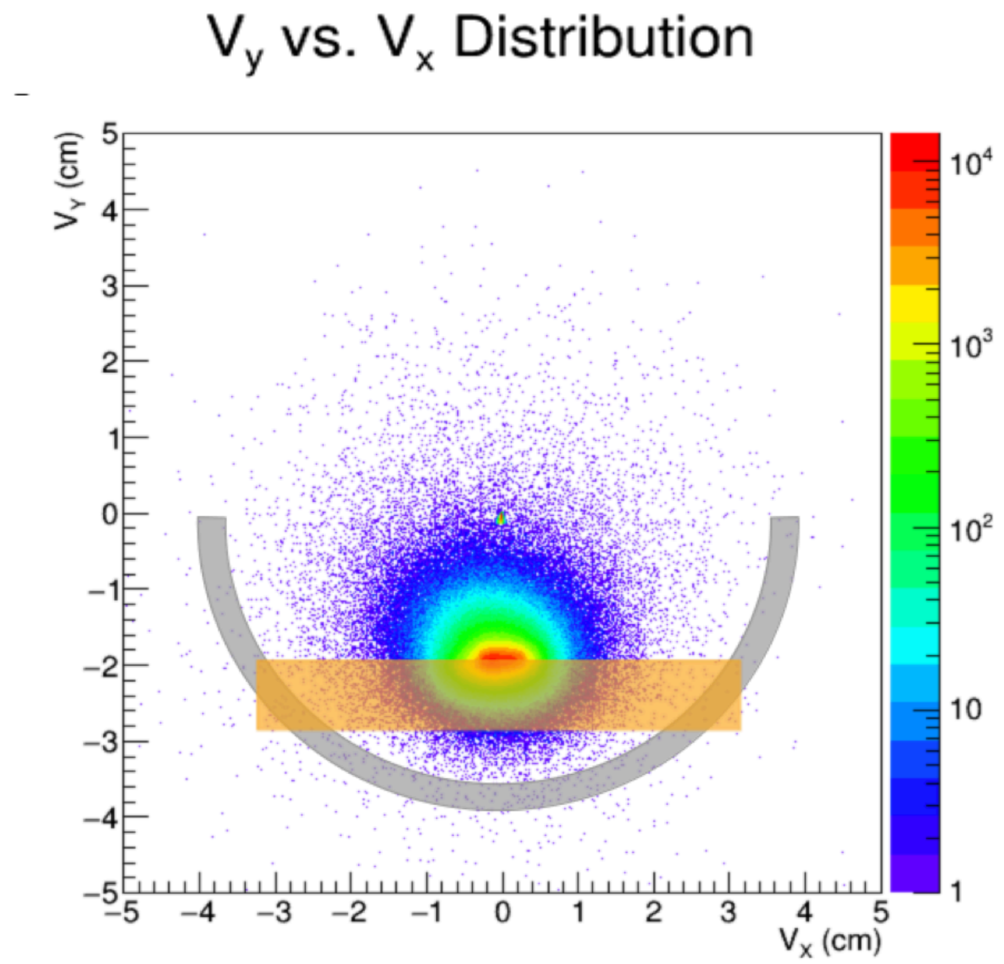
- RHIC BES covers a wide region of baryon density
  - Look for the onset of de-confinement, phase boundary, and location of possible critical point

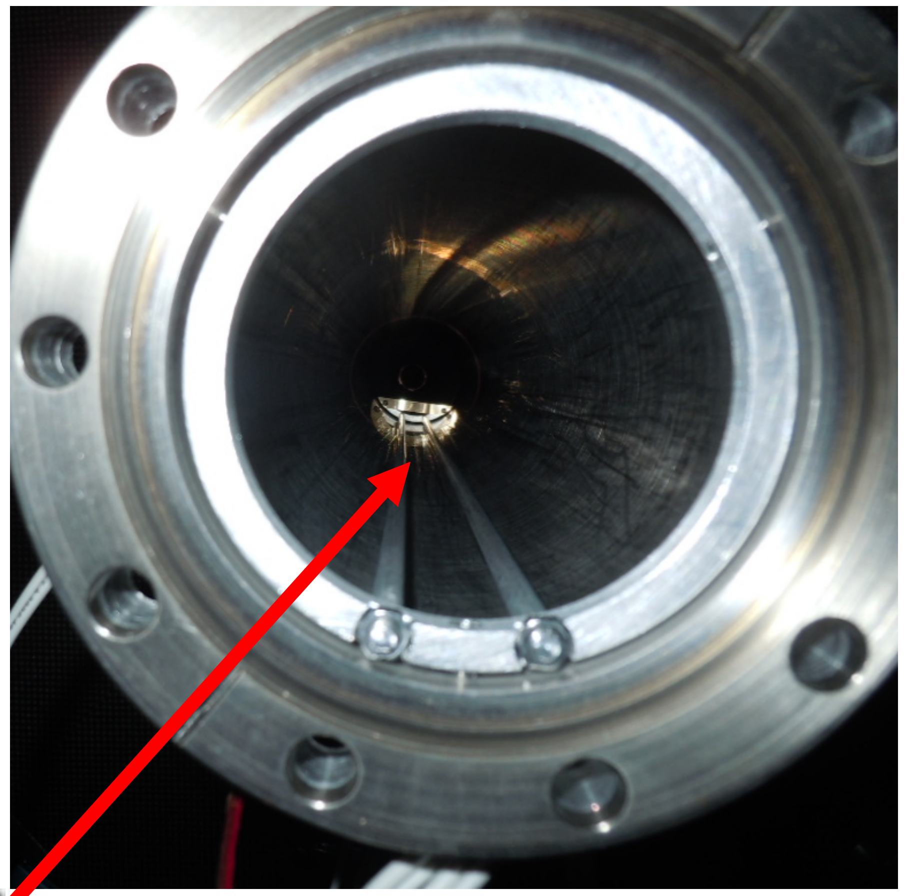
- STAR FXT mode $\sqrt{s_{NN}}$ = (3.0 - 7.7) GeV
  - High baryon chemical potential μ_B (~400 MeV up to ~ 750 MeV) allows us to study the properties of high baryon density matter
  - Strangeness can be used to study medium properties at low collision energies

FXT setup at STAR

- Target was installed at the edge of TPC
- 260M events for Au+Au FXT at $\sqrt{s_{NN}}$ = 3 GeV (year 2018)
- Good mid-rapidity coverage





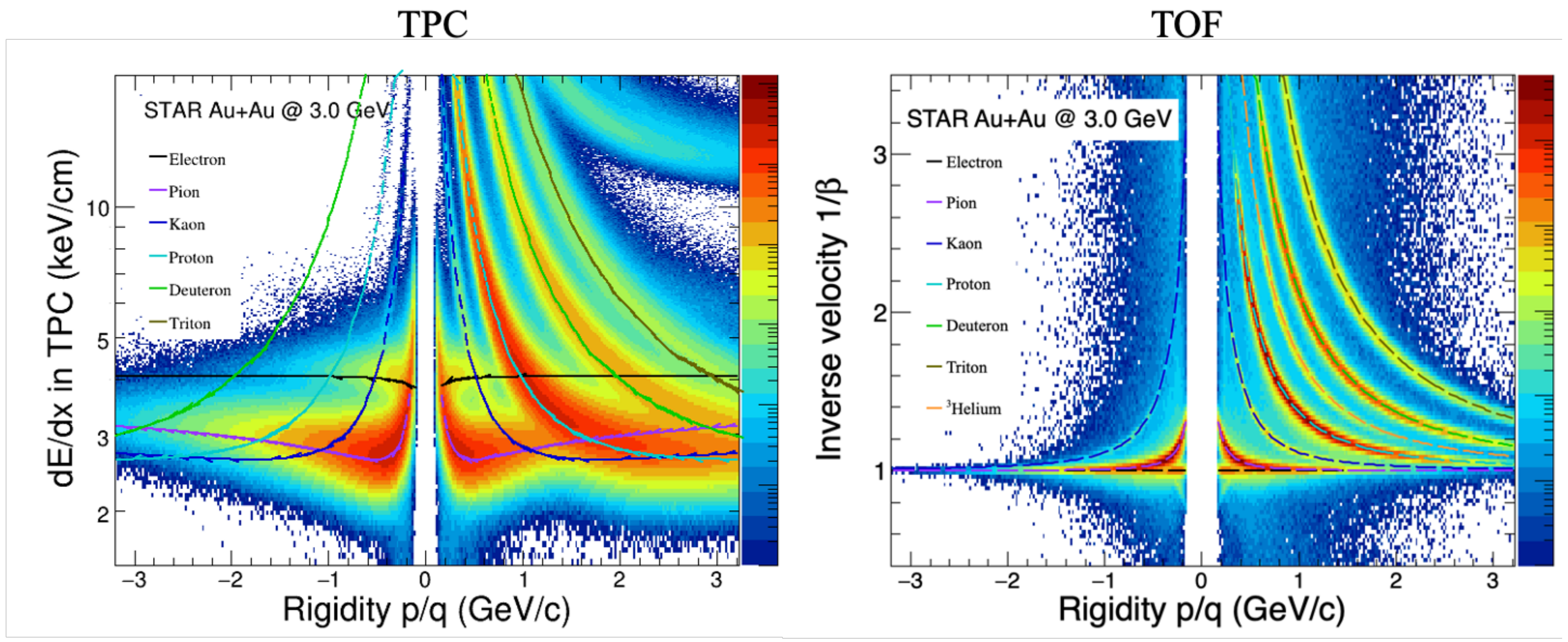


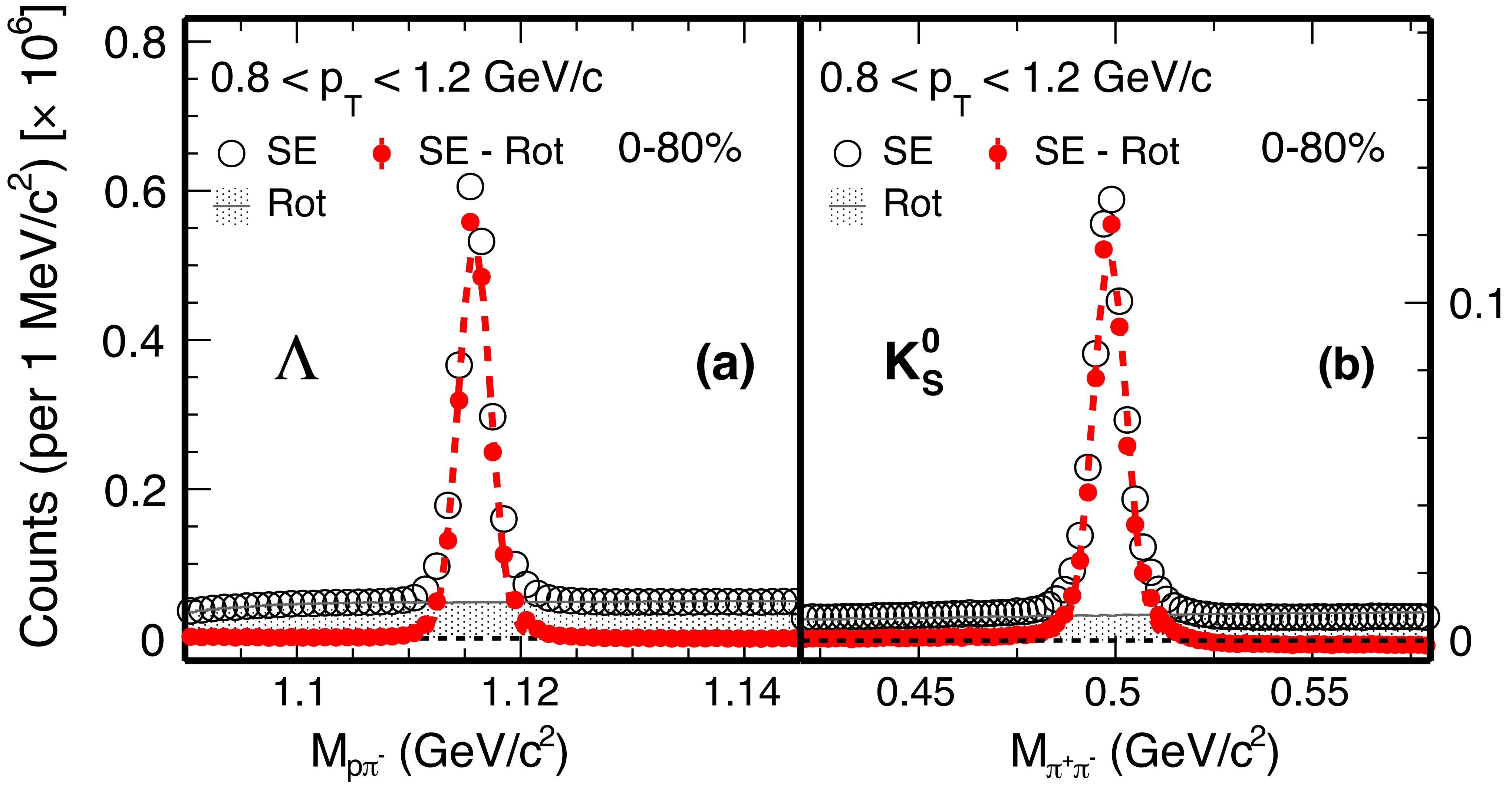
Beam pipe

Au-Target = 0.25mm thickness
1% interaction probability

Conventions:
beam-going direction is the positive direction
In C.M. frame, $y_{target} = -1.045$ for the 3 GeV collisions

Particle identification and reconstruction

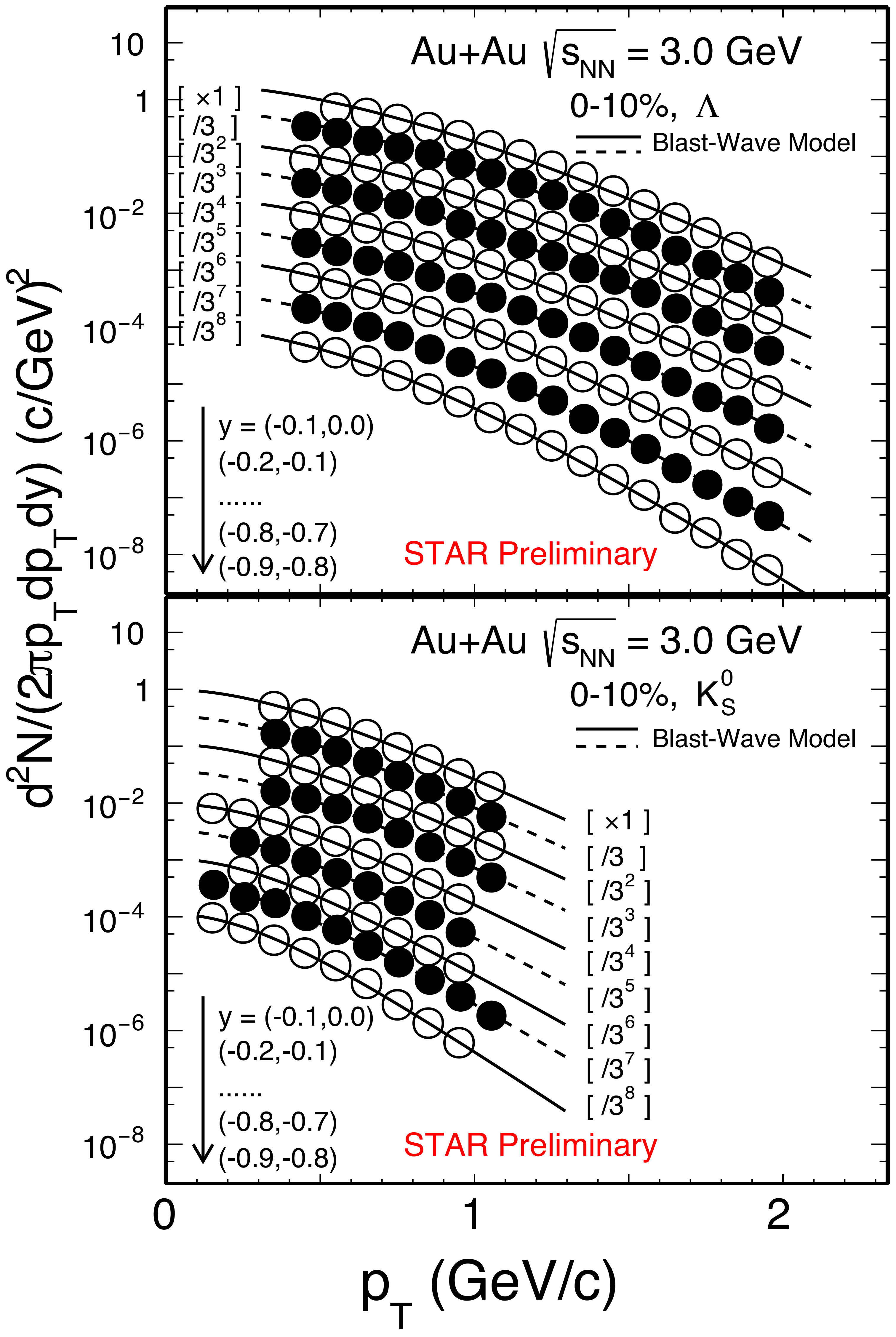




- **TPC (dE/dx) and TOF (β) for pion, kaon and proton identification**
- **Reconstruct the short-lived particle $\Xi^-, \phi, \Lambda, K_S^0$ via a hadronic decay channel**
  - $\phi \rightarrow K^+K^-$, $\Xi^- \rightarrow \Lambda(p\pi^-) + \pi^-$, $K_S^0 \rightarrow \pi^+\pi^-$
  - KF Particle package is used to improve the signal significance
- **The combinatorial background is reconstructed by the rotation method**

KF Particle Finder: M. Zyzak, Dissertation thesis, Goethe University of Frankfurt, 2016

Efficiency corrected p_T spectra



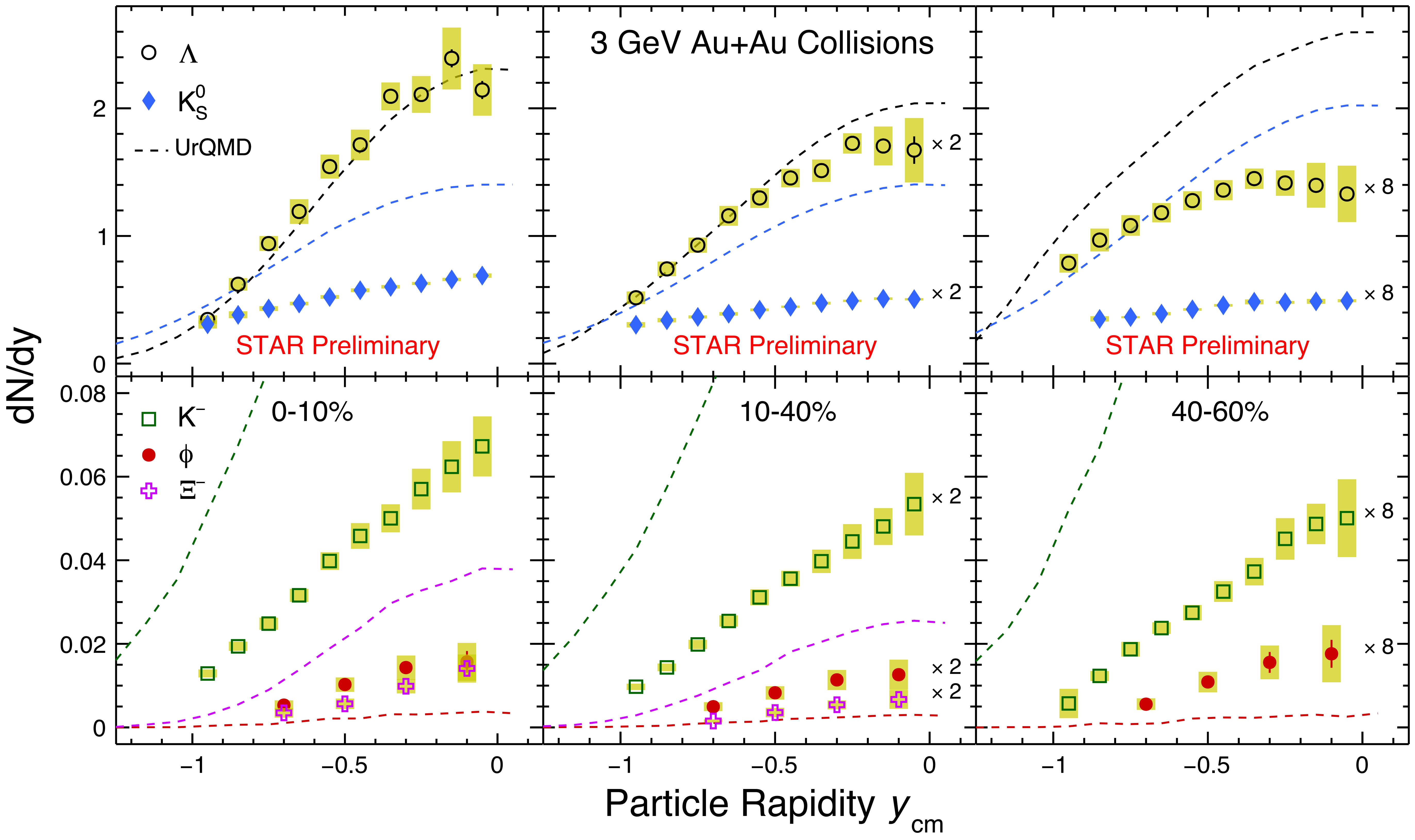
- **Tracking efficiency and detector acceptance are estimated with GEANT simulations embedded into real events**
- **Λ and K_S^0 invariant yields in 0-10% centrality for various rapidity regions**
- **Low p_T extrapolation: Blast-Wave function**

$$\frac{d^2N}{2\pi p_T dp_T dy} = A\int_0^R r dr m_T \times I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right)K_1\left(\frac{m_T p \cosh\rho(r)}{T_{kin}}\right)$$

T_{kin}: the kinetic freeze-out temperature
$\langle\beta_T\rangle$: average transverse radial flow velocity
n: the exponent of flow velocity profile, n=1
I_0 and K_1 are from Bjorken Hydrodynamic assumption

- **Alternative fit functions are used in order to estimate the systematic uncertainty in dN/dy**

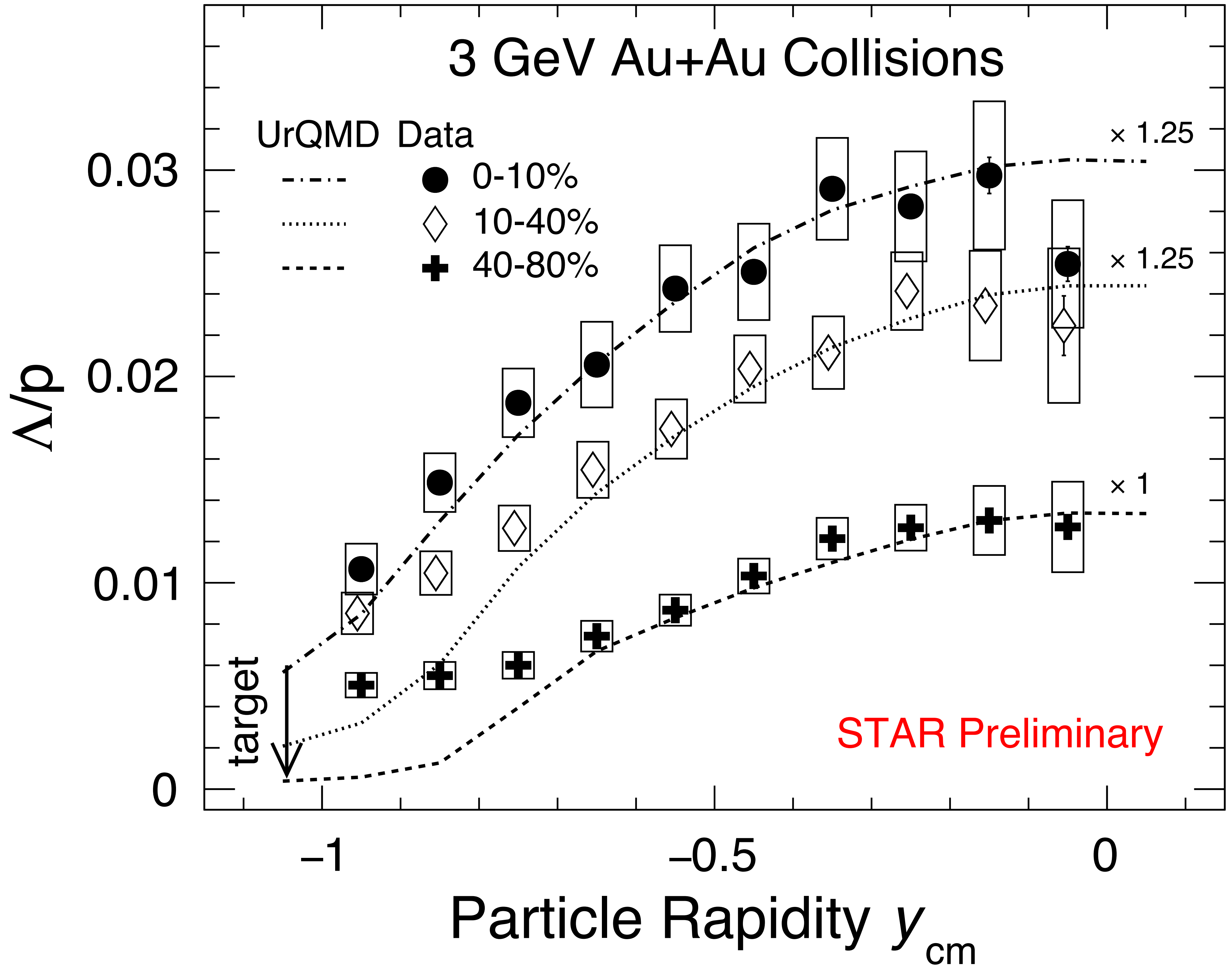
Centrality and rapidity dependence of yields



Phys. Lett. B 831 (2022) 137152

- **Rapidity dependent yields obtained from integrating data and Blast-wave function (or m_T exponential function) fits of spectra for the unmeasured region**
  - **y_{cm} range will be extended by eTOF & iTPC upgrade**
- **UrQMD reproduces the yields of Λ except in the 40-60% centrality bin, but overestimates Kaons, Ξ^- and underestimates ϕ mesons**

Centrality and rapidity dependence of particle ratio

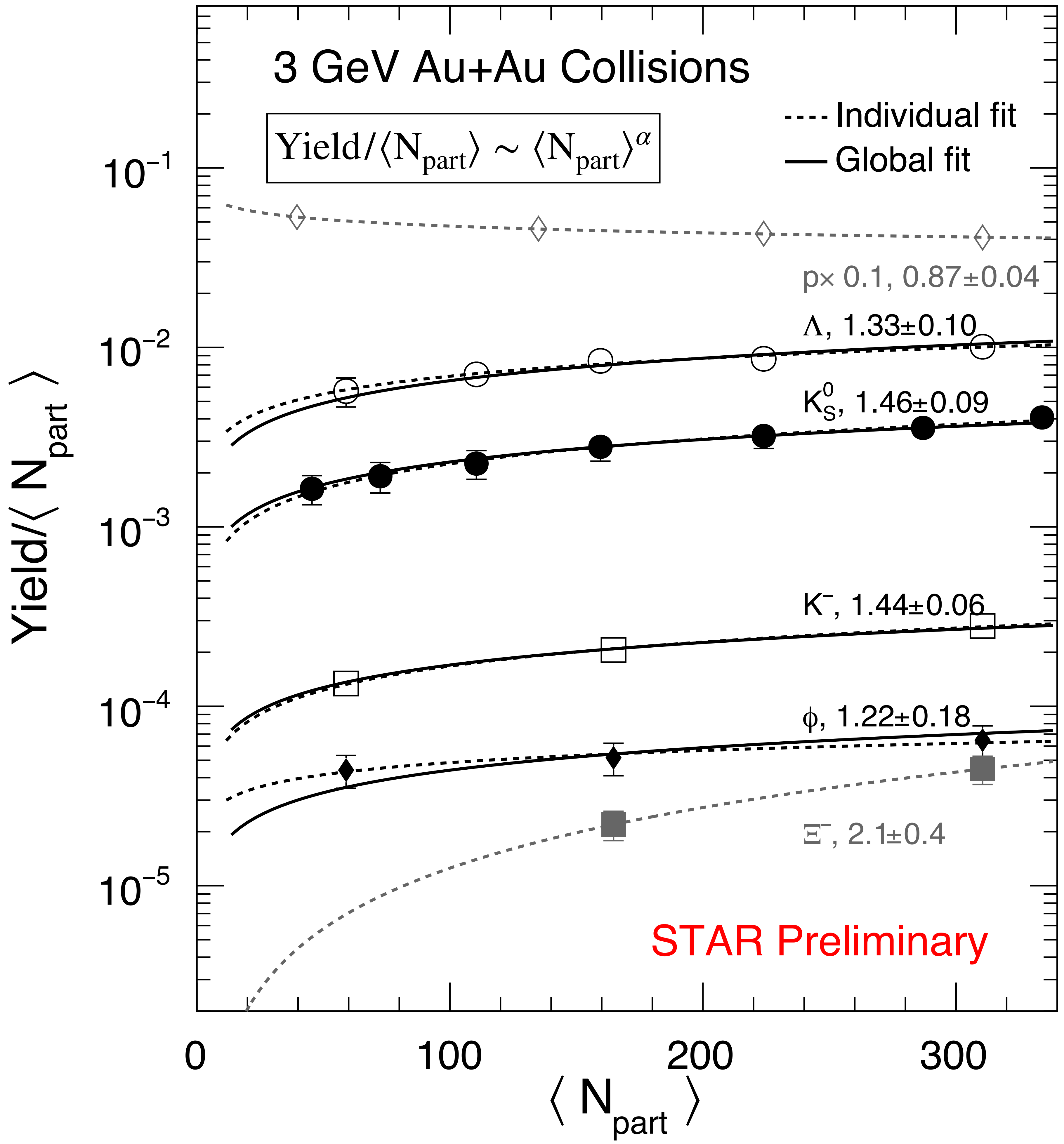


UrQMD: 0-10% and 10-40% centrality are scaled up by 25%

- Enhanced production of Λ at mid-rapidity compared to target rapidity
- UrQMD model underpredicts those ratios but can describe the trend of the data
- Comparison with hypernuclei to light nuclei ratios help us gain insight into hypernuclei and light nuclei production mechanisms

See talk from Yuanjing Ji, Jun 14, 2022, 11:30 AM

Strangeness production vs $\langle N_{Part} \rangle$



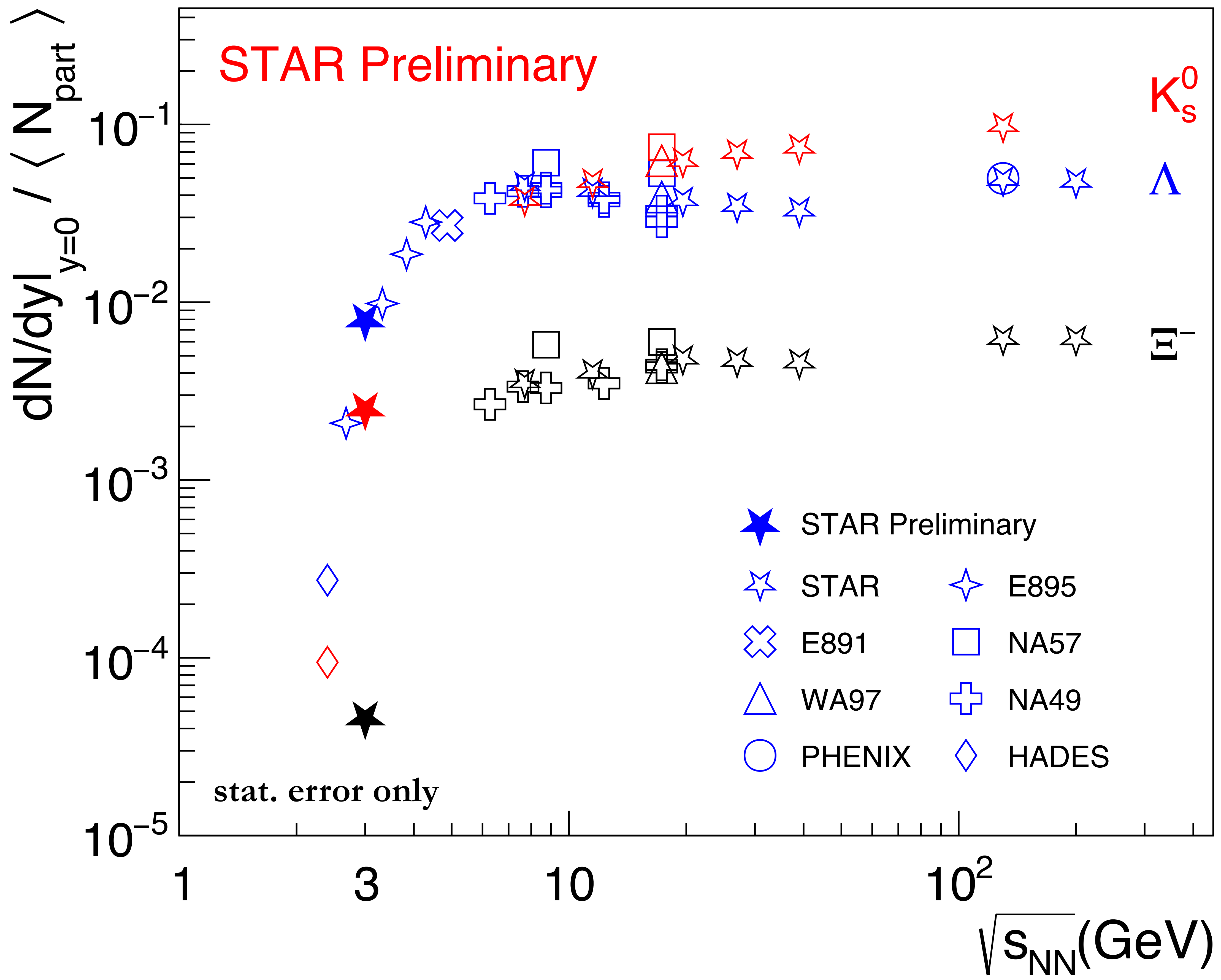
- **Universal centrality dependence of strangeness production**
  - Increase with centrality
  - Strangeness yield (K^-, K^0_S, ϕ, Λ) $\propto \left\langle N_{\mathrm{part}} \right\rangle^{\alpha}$, $\alpha = 1.42 \pm 0.04$

- **Ξ^- seems to deviate from the scaling trend**
  - Ξ^- is different from other hadrons due to its multi-strange-quark content and sub-threshold production

- **Proton has a different trend**

K^0_S $\sqrt{s_{thr}}$ ~ **2.55 GeV**
Λ $\sqrt{s_{thr}}$ ~ **2.55 GeV**
ϕ $\sqrt{s_{thr}}$ ~ **2.89 GeV**
Ξ^- $\sqrt{s_{thr}}$ ~ **3.25 GeV**

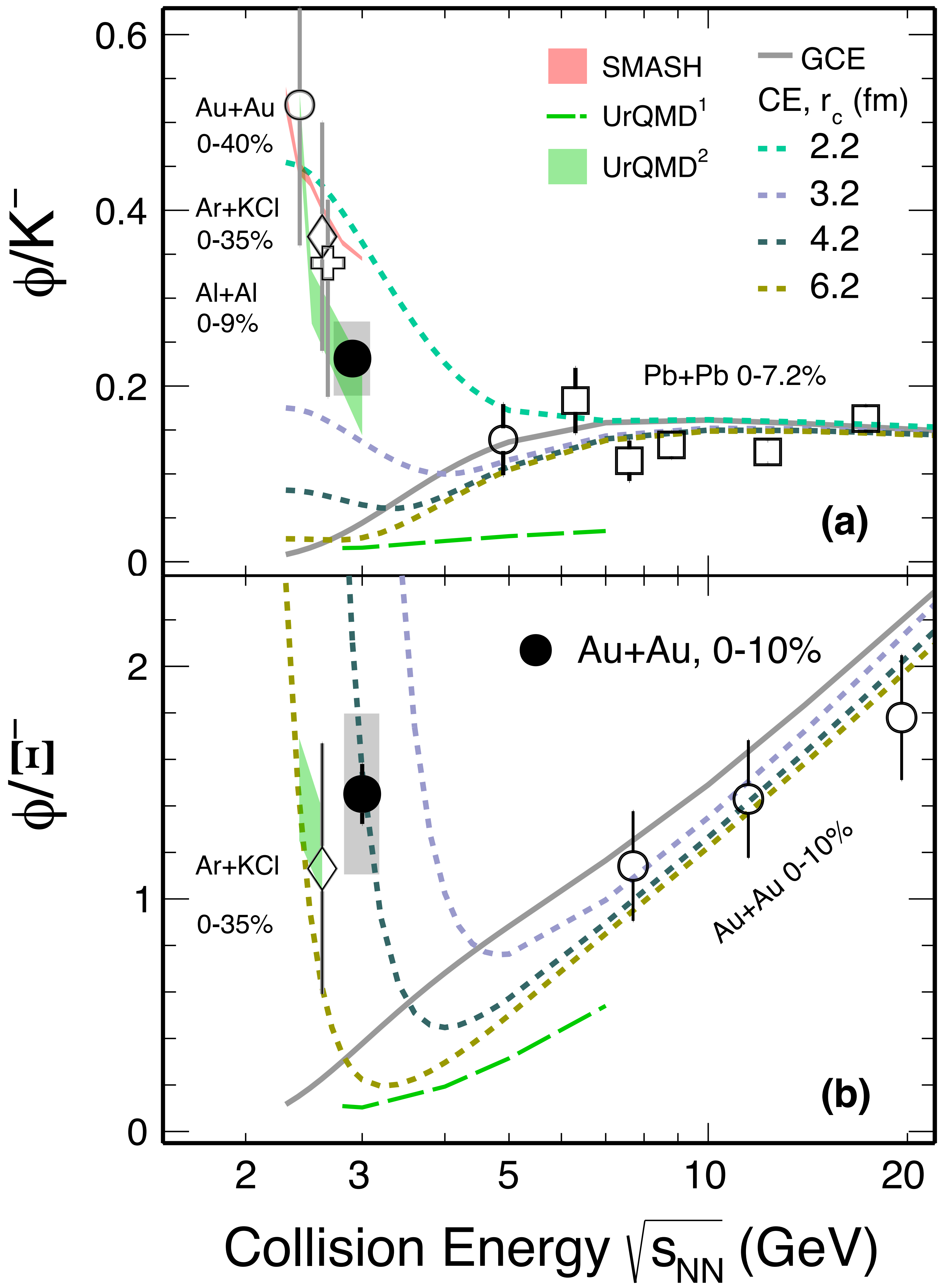
Strangeness production vs $\sqrt{s_{NN}}$



Data compilation: C. Blume Prog.Part.Nucl.Phys. 66 (2011) 834-879
HADES: Phys.Lett.B 793 (2019) 457-463, 2019

- **STAR FXT dN/dy consistent with the Λ, K_S^0 trends demonstrated by published data**
- **First sub-threshold Ξ^- measurement in Au+Au collisions**
- **Expect more results at low energies from additional high statistics BES II data sets**

Particle ratios vs $\sqrt{s_{NN}}$



- **Local strangeness conservation is required!**

➡ **GCE to CE transition!**

- **Default UrQMD failed to describe the measurement at low energies**

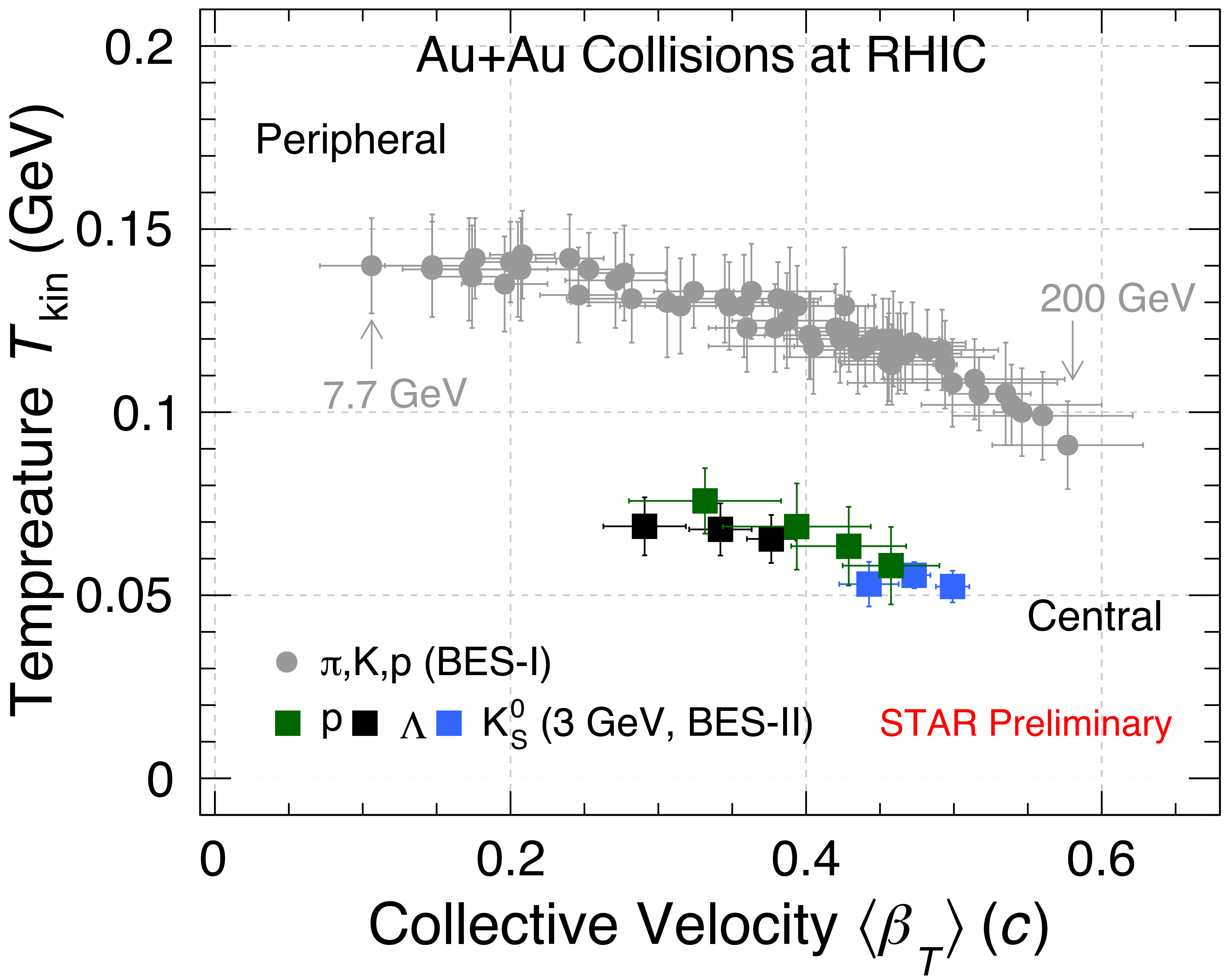
- **Transport models with high-mass resonance decay to ϕ and Ξ^- (modified UrQMD and SMASH) can reasonably describe data at low energies**

UrQMD[1]: the public version
UrQMD[2]: the modified version

r_c: correlation length, radius of the volume inside which the production of particles with open strangeness is canonically conserved

Data compilation:
STAR: Phys. Lett. B 831 (2022) 137152, Phys. Rev. C 102 (2020) 34909
HADES: Eur. Phys. J. A (2016) 52: 178
UrQMD[1]: Prog. Part. Nucl. Phys. 41 (1998) 225-370
UrQMD[2]: J. Phys. G: Nucl. Part. Phys. 43 015104
Thermal CE: Phys. Lett. B 603, 146 (2004)

Kinematic freeze-out properties



Phys. Rev. Lett. 108 (2012) 72301
Phys. Rev. C 102 (2020) 34909

- **Kinetic freeze-out temperature ($T_{\rm kin}$) of Λ is systematically higher than that of K_S^0 at 3 GeV**
- **$T_{\rm kin}$ of Λ and K_S^0 at 3 GeV is lower than π, K, p at higher energy collisions**

➡**Similar observations for protons and deuterons, implying different EOS at freeze-out**

Summary

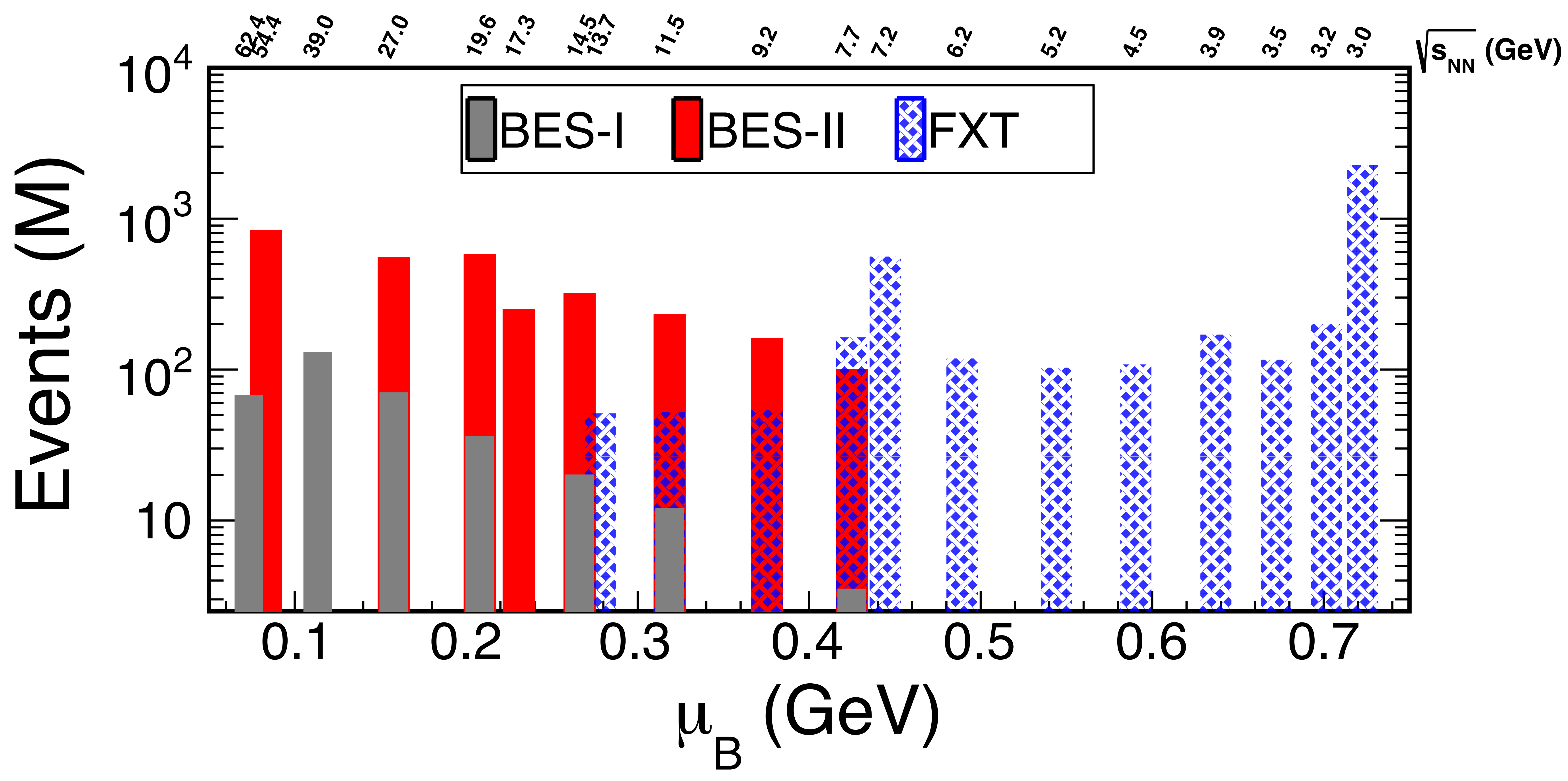
- Presented measurements on strangeness production in 3 GeV Au+Au collisions
  - Precise centrality & rapidity dependence of yields
  - ϕ/K^- and ϕ/Ξ^- show a strong effect of canonical suppression Phys. Lett. B 831 (2022) 137152
  - Λ and K_S^0 spectra indicate lower kinetic freeze-out temperature than π, K, p at higher energy collisions

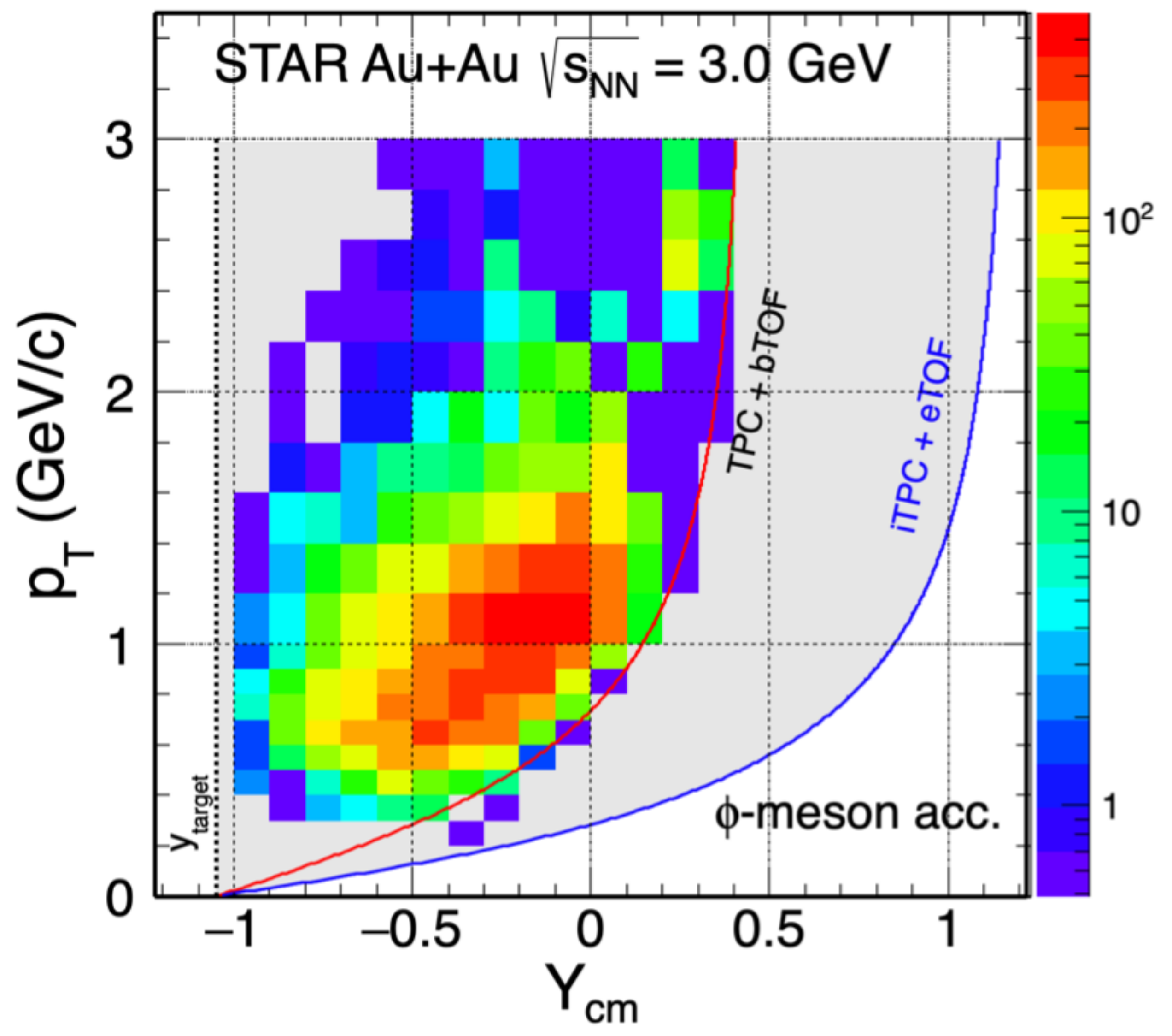
- At 3 GeV, the measured v_2 for all particles are negative and the NCQ scaling breaks, especially for positive charged particles Phys. Lett. B 827 (2022) 137003
- The suppression of C_4/C_2 is consistent with fluctuations driven by baryon number conservation which indicates a hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV Phys. Rev. Lett. 128 (2022) 202303
- The freeze-out parameter ($T_{\rm kin}$) of deuteron is systematically higher than that of proton at 3 GeV, which is different from higher energies Hui Liu, QM 2022

➡ **All results from 3 GeV Au+Au collisions: particle production mechanism dominated by hadronic interactions**

Outlook

- Strange hadron yields together with π, K, p will be used for chemical equilibrium models to determine T_{chem} and μ_B
- High statistics data in STAR BES II $\sqrt{s_{NN}}$ = 3 - 27 GeV, iTPC+eTOF
  - Extract freeze-out parameters
  - Analyze baryon correlation functions
  - Analyze hyper-nuclei production and collectivity
  - And more …





See poster from Sameer Aslam, Jun 14, 2022, 5:10 PM